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Detection and Jamming of LPI Radars

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1.0 INTRODUCTION

Low Probability of Intercept (LPI) radar describes a class of radars that have been purposefully designed to be difficult to detect by hostile receivers. Discussions of LPI radar invariably centre around the various modulations that can be impressed on a radar waveform to mask its presence. However, the term LPI can also be used to describe techniques such as antenna sidelobe reduction and active power management that also hinder a hostile receiver from detecting the presence of a threat radar.

Although it would be desirable to have a radar that was totally undetectable by the platform that is being observed, this is a goal that is very difficult to achieve. There are areas of the engagement that favour the jammer; these can be exploited by the target platform to reduce the risk of being engaged by an LPI radar. For instance, the power received by a jammer varies as R^{-2} whereas the power received by the radar varies as R^{-4} giving the jammer an R^2 advantage. In addition, the radar must cope with fluctuating target characteristics that can increase the required received power in order to process and declare a detection by as much as 8 dB.

There are many applications for LPI radars. Due to the dynamics of the engagement, air, land and maritime applications are quite different from each other. The main application for the air environment is covert operation in hostile territory in order to avoid, or at least delay detection which would alert enemy defences. Functions performed by such LPI radars are primarily navigation, terrain avoidance and missile approach warning. LPI technology is a natural complement to stealth technology and hence is found on the US F-22 and on the Soviet Su-37. Target designation and fire control are also potential applications, but as explained later in this report, the dynamics of an air-to-air engagement and the small target radar cross sections make true LPI operation somewhat difficult and capable of fairly limited range. In this case, it may be feasible to detect and jam such LPI radars with only minor modifications to current jammer designs.

There are land based applications for LPI search and targeting radars, especially for use against helicopters and fighters which could be alerted by conventional radars and quickly return fire with guns or anti radiation missiles. One example is the French Crotale which proved difficult to detect with current jammer technology at previous NATO TRIAL MACE sorties. This radar is a classic

example of the effectiveness of power management techniques in reducing detection range by a hostile platform.

The naval environment has LPI radar applications as well, including seekers for anti-ship missiles and search/track functions on shore based, littoral weapon systems. The maritime application is expected to provide the biggest challenge for the jammer, since ranges are typically very short and ships have notoriously large cross sections allowing the radar transmitter power to be extremely low. LPI technology could easily be combined with other emerging technology areas. For instance, the combination of LPI and MMW technologies makes an especially formidable weapon system in the naval environment.

By investigating the design constraints imposed on the LPI radar designer and understanding the ultimate requirement to detect and track targets of varying cross section and mobility, it can be shown that there are options for the jammer designer that will lead to a capability to detect and jam LPI radars.

This report summarises some of the techniques used by designers to make radar signals difficult to detect by hostile receivers. Examples of currently fielded LPI radars are presented which demonstrate the need for additional work in developing ECM receiver architectures that can deal with the emerging LPI threat. Finally, a modification to the current SDLVA detection process used in the CARDS testbed is proposed which may improve jammer sensitivity to LPI radar signals by up to 20 dB.

2.0 LPI RADAR TECHNIQUES

There are several LPI radar techniques available to the modern radar designer that may be used singly or in various combinations, depending on the application. Reducing the radar's peak ERP by using some form of pulse compression technique is the most common and almost universal LPI radar technique. The objective is to spread the radar's signal over a wide bandwidth over a period of time. This is typically done with modulation such as linear FM chirp, phase coding or frequency hopping. Other LPI techniques include power management techniques such as limiting the target illumination time, controlling antenna sidelobes and using pseudo-random intervals between target illuminations.

2.1 FM Chirp

Pulse compression allows a radar to lower its peak transmit power and still maintain high average power and range resolution - these are necessary ingredients for an LPI radar. FM chirp is the most common and the simplest pulse compression technique to implement. It can be applied to both pulsed and CW radars and refers to a process in which the radar transmit frequency is changed linearly over time. The result is a wide pulse width, T, that occupies a given bandwidth, B. In the receiver the chirp return is processed using a matched filter which compresses it by collapsing the pulse upon itself thereby increasing the range resolution. This is usually done using a dispersive filter in which the time delay through the filter is a linear function of frequency matched to the transmit waveform. Filters of this nature are frequently constructed using surface acoustic wave (SAW) technology. The compression gain available from chirp schemes is also called the time-bandwidth product, TB. According to Brookner, Ref. 9, typical time-bandwidth products range from 50 to 3000, but gains as high as 500,000 have been obtained. These numbers may well have changed in the 20 years or so since Brookner's survey, and it is recommended that a review of the classified literature be part of any follow-on work to ascertain where the technology has taken the current threat.

Linear FM waveforms have two definite disadvantages:

(1) range-Doppler cross coupling, resulting in measurement errors unless one of the co-ordinates, range or Doppler, is known; and
(2) they produce time (or range) sidelobes that are quite high (-13.2 dB).

Range-Doppler cross coupling refers to the effect of the target Doppler shift on the radar processor. Since the transmitted waveform is itself shifting in frequency, any target motion that produces significant Doppler shifts will cause an error in the received frequency and therefore an error in the range measurement. These errors can be reduced somewhat with compensation of the target Doppler shift before processing the return.

Range sidelobes pose a large problem because they can mask a small target. They can be reduced by applying various weights to received signal, but this results in a 1 or 2 dB loss in SNR and a decrease in the resolution. Table 1 shows some characteristics of commonly applied weighting functions.

Table 1: Characteristics of Some Common Weighting Functions

Weighting Function	Maximum Sidelobe Level (dBc)	Relative Width of Mainlobe	Relative SNR (dB)
No Correction	-13.2	1.0	0
Hamming	-42.8	1.5	-1.34
Cosine-Square	-31.4	1.59	-1.76
Cosine-Cube	-39.1	1.41	-2.38
Dolph-Chebyshev	-40	1.41	-

Phase weighting can also be applied to both the transmitted and the received signals in a process referred to as non-linear FM. This technique avoids the SNR loss seen in linear FM processing, has low range sidelobes but is more sensitive to Doppler shifts than linear FM waveforms and is difficult to implement.

In general, linear FM is a poor choice for an LPI waveform for two reasons:

1. The instantaneous bandwidth of the signal is small and allows a narrowband receiver to detect the presence of the radar and,

2. The waveform is not programmable and a receiver only needs a small fraction of the chirp in order to calculate the slope and thereby derive some processing gain.

Dillard and Dillard, Ref. (4), state that linear FM is generally used for other than covert operation, since the pulses can be easily detected with a matched filter provided the slope is constant. This appears to contradict claims of several radar manufacturers of FMCW "LPI" systems. However, if the application allows for long integration times of several milliseconds, the radar can obtain high compression gain and this, coupled with the low ERP, may well make the radar difficult to detect by the target using conventional EW receivers. This is in fact the case in maritime (littoral) surveillance or navigation applications.

2.2 Phase Codes

FM chirp techniques make use of fairly simple analog processing. In contrast, digital techniques such as phase coding of a signal within a pulse can be used to yield processing gain using fairly simple digital processing techniques that are greatly enhanced by the availability of inexpensive digital signal processors. Phase codes can be broken down into 2 main categories:

- binary phase codes and,
- polyphase codes.

2.2.1 Binary Phase Codes

Binary phase codes are very easy to generate using digital techniques. The transmitted pulse is broken into small segments or chips. Each chip is assigned a phase of either "+" or "-". "+" indicates that the chip is transmitted with zero phase shift while "-" indicates that the chip is transmitted with a 180° phase shift. The binary nature of the code means that simple techniques such as frequency doubling can be used to remove the phase code from the pulse and thereby increase the power available to a hostile detector. Phase coded waveforms exhibit the same range sidelobes seen in FM chirp signals and mathematicians have spent years developing codes to minimise them. Three codes that have been developed and are commonly seen in use today are the Barker codes, compound Barker codes and pseudo-random codes.

2.2.2 Barker Codes

Barker codes are a set of codes which exhibit very low range sidelobe performance. Barker codes have been found that consist of from 2 to 13 bits as

shown Table 2. It should be noted that "+" and "-" values can be reversed and the waveform will maintain the same properties.

Table 2: Barker Codes

Code Length	Code	Range Sidelobe Level (dB)	Processing Gain (dB)
2	+ - OR + +	-6.0	3.0
3	+ + -	-9.5	4.8
4	+ + - + OR + + + -	-12.0	6.0
5	+ + + - +	-14.0	7.0
7	+ + + - - + -	-16.9	8.5
11	+ + + - - - + - - + -	-20.8	10.4
13	+ + + + + - - + + - + - +	-22.3	11.1

The compressed output of a 3-bit Barker code is shown in Figure 1 which shows the relative position and weights of the range sidelobes. It is clear from this figure how easily small targets could be masked by the range sidelobes produced by larger targets in other range bins.

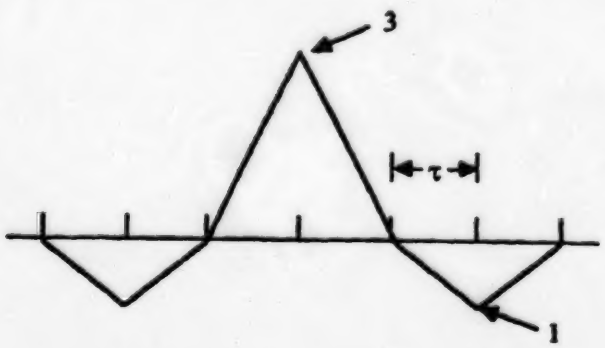

Figure 1: Compressed Output of 3-bit Barker Coded Pulse

There are 2 major disadvantages associated with Barker codes. The first is that the maximum length is 13; despite years of research, mathematicians have been unable to discover longer codes that exhibit the same desirable properties as the existing Barker codes. If, as is the case in LPI radar, it is desired to transmit a

very wide pulse and still maintain good range resolution, then longer code lengths are required. The second disadvantage is that they are quite sensitive to target Doppler. This is particularly a problem when the radar target is a high speed aircraft that impresses a considerable Doppler shift to the radar return. In order to demonstrate the sensitivity of these codes to Doppler, consider the case of a 7-bit Barker coded radar pulse width of 50 μs and a target which causes a 10 kHz Doppler shift to the radar return. This Doppler shift corresponds to a phase shift of 10,000 x 360°per second or 3.6° per μs. Over the 50 μs pulse a total phase shift of 180° will develop. The resulting output from the matched filter is shown in Figure 2 for the ideal case when the Doppler shift is 0 and for when the Doppler shift is 10 kHz. The effect of coherent integration of the 7 segments in the coded pulse is shown. Clearly there is a considerable loss (about 5 dB) from the introduction of only 180° phase shift.

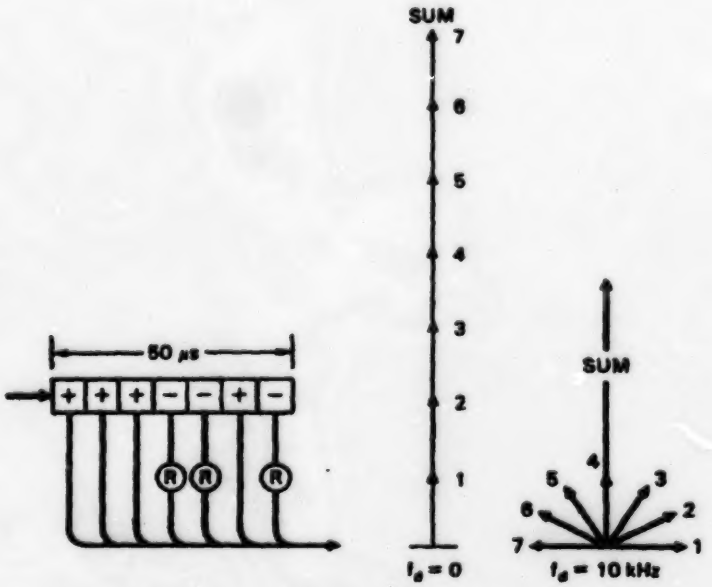

Figure 2: Effect of Doppler Offset on Binary Code

The effects of Doppler shift can be offset somewhat in the radar by using Doppler tuning techniques to compensate for the target Doppler shift. In so doing, an estimate of the target Doppler is used to reduce the size of the phase error, however, it will not be eliminated completely.

2.2.3 Compound Barker Codes

While trying to alleviate the disadvantage associated with the limited length of the Barker codes, it was discovered that it was possible to embed one Barker code within another, as shown in Figure 3, to create a compound Barker code. These codes have the advantage that virtually infinite length code can be created and hence range resolution for long pulses can be enhanced and that high levels of processing gain can be achieved.

An important fact to note is that the sidelobe levels of the compound Barker codes do not improve with code length; they are identical to the sidelobe level of the component code. For example, the 9-bit compound Barker code shown in Figure 3 posses the same sidelobe levels as the 3-bit Barker code that it is composed of. In contrast, the gain associate with the processing does increase as the code length increases. Referring to the same example, the 3-bit Barker code only delivers a gain of 3.8 dB however the 9-bit compound Barker code yields a 9.5 dB gain.

+			+			-			**Primary Code**
+	+	-	+	+	-	+	+	-	**Embedded Code**
+	+	-	+	+	-	-	-	+	**Resulting Compound Code**

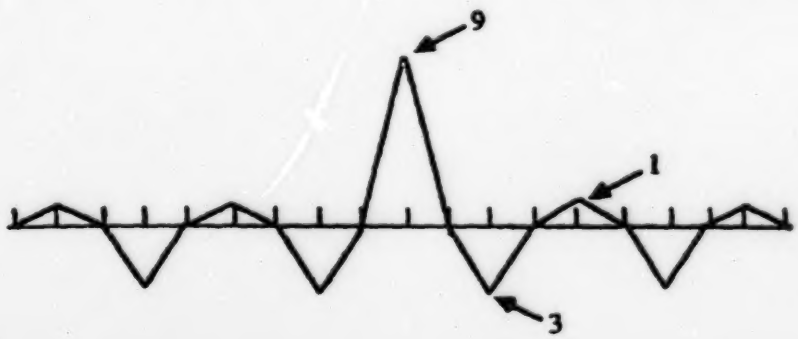

Figure 3: Compressed Output using 9-Bit Compound Barker Code

2.2.4 Pseudo-Random Codes

Pseudo-random or pseudo-noise (PN) codes are a third class of binary codes that are easily generated digitally using a feedback register techniques. These codes are sometimes referred to as maximal length codes because they offer enhanced performance when compared to Barker codes. In fact, a maximal length code of N=3 has performance similar to that of a 7-bit Barker code. Unfortunately, unlike the Barker codes whose sidelobe levels decrease with N^2, the sidelobe levels of these codes only decrease linearly with N. These codes possess 3 key features that make them attractive for use in an LPI system though:

(1) They are less susceptible to Doppler effects than Barker codes
(2) The spectral content is noise-like
(3) The feedback register makes them programmable.

Although, the spectral content of a PN coded signal is noise-like, the fact that the phase transitions are binary allows a hostile receiver to make use of frequency doubling to remove the coded structure and thereby detect the signal.

2.2.5 Poly-Phase Coded Radars

Poly-phase coded signals were conceived as the ultimate in coded waveforms. Whereas binary phase codes allow for only 2 possible values of phase, there is no theoretical limit as to how many phase levels can be implemented when using a poly-phase code. The spectral content of the signal is shaped by the specifics of the code and can be made to be almost uniform across a given bandwidth giving the signal a characteristic that is hard to detect by automatic means. The first poly-phase code put into radar service was a Frank code which was developed for use in the Loran-C system.

The major disadvantage of this kind of code is that as the phase increment becomes smaller, the equipment needed to generate them becomes more complex and therefore more costly. In addition, the resulting processing is more sensitive to Doppler shifts. This property will restrict both the number of phase levels employed by the waveform and the applications where it can be used. For example, these codes would not be appropriate for use in air-to-air or supersonic missile seeker applications without the use of Doppler compensation because the resulting Doppler shifts would make processing of the codes too difficult. Fortunately for the radar designer, Doppler compensation is a poly-

phase process and can be implemented within the radar processor. The ability of the processor to perform the compensation will be a limiting factor in the performance of these codes however.

Just as frequency doubling can be used to assist with the detection of a binary coded pulse, higher order frequency multiplication can be used to demodulate poly-phase coded signals. For instance, a quintupler can be used to demodulate a five level poly-phase coded pulse. The idea of having a series of multipliers each having the capability to process one type of poly-phase code may be theoretically possible but it would be cumbersome and costly and therefore not practical.

The initial, uncompressed bandwidth of a phase coded radar is nominally the reciprocal of the chip width. The phase coding spreads the signal more or less uniformly over that entire bandwidth. Thus, it is important that the jammer's RF bandwidth be wide enough to cover all, or at least most of, the radar's agile bandwidth. In modern radars, this can be on the order of several hundred MHz.

2.3 Power Management

Power management is a radar technique that is becoming more practical with the improvements in digital signal processing. Power management encompasses a host of techniques including:

- Antenna sidelobe control/suppression
- Pseudo-random illumination of a target
- Dynamic control of transmitter power to maintain a minimal signal -to-noise ratio (SNR)

These techniques can be quite effective in making a radar difficult to detect by a hostile receiver.

The French CROTALE system makes effective use of power management. Shortly after lock-on, the tracking radar reduces its transmitter power such that the SNR of the received level is kept to a minimal value. This process is continued during the course of the engagement reducing the range at which the target is able to detect the presence of the radar.

3.0 LPI RADAR APPLICATIONS AND EXAMPLES

During the course of this work, a brief review of the open literature was conducted. It revealed some interesting examples of LPI radar for air, maritime and land applications.

This was not meant as a threat study or to delve into great detail on any systems in particular. The purpose of this review was simply an attempt to get a feel for the current state of LPI technology – has it progressed to the point where it has been demonstrated and accepted as a viable technology? What applications are suited for its use? And where might future applications surface?

3.1 Airborne LPI Radars

The primary application envisaged for an airborne LPI radar is that of covert navigation. This is primarily driven from the popularity of present day stealth programs. It would be desirable to have a stealth bomber or fighter capable of entering a hostile region using its radar for navigation and not have its presence detected by enemy RWR or ESM receivers. Examples of radars performing this function include:

(1) AN/APG-77 (F-22),
(2) AN/APQ-183 (A-12 AVENGER),
(3) AN/APQ-181 (B2-A),
(4) LONGBOW (Apache)
(5) Sukhoi S-37 multi-role fighter radar
(6) LANTIRN (Navigation/Targeting pod used on F-14, F-15 and F-16.

It is hard to imagine other LPI applications on an airborne platform as the typical high speed dynamics of most airborne applications do not permit the long integration times needed to significantly reduce the transmitter power. In order to obtain coherent integration, the target must remain in the same range resolution cell for the period of the integration. Also, some processing techniques are very sensitive to Doppler frequency and would therefore yield poor results.

3.2 Maritime LPI Radars

Just as LPI was useful for covert navigation for air applications, it is equally useful for covert maritime applications. LPI is well suited for this application as the relatively slow speed of the ship allows for long integration times – this makes a real LPI capability possible since targets remain in the same range resolution cell for extended periods of time permitting the long dwells which yield high processing gain. In addition, ship targets are characterised by extremely large radar cross-sections that further reduce the power required by the radar transmitter. The best example of a maritime LPI navigation radar is the Signaal SCOUT. This radar has been procured and is in use by several navies for use on low cross section corvettes and fast patrol craft.

Another application that is well suited to LPI technology is that of the anti-ship missile (ASM) seeker. Although the speed of the missile does reduce the amount of time available for integration, most ASM's are subsonic and the large radar cross section presented by conventional surface vessels makes true LPI operation possible. Saab of Sweden is currently testing and marketing an LPI seeker with its RBS-15 mk3 ASM. This seeker reportedly employs a low power transmitter and dynamic power management techniques. In addition, the seeker infrequently paints its targets to help decrease the probability of detection by its target. This is a promising area of technology and undoubtedly there will be further developments from other manufacturers as LPI missile seekers have little to fear from either soft kill ECM or hard kill close in weapon systems if they cannot be detected.

3.3 Land Based LPI Radars

There are quite a few examples of land based LPI radar generally performing one of two functions:

- ground surveillance or,
- short range air surveillance.

In the case of the ground surveillance role, these radars can be used to covertly detect ground targets because long integration times are possible. In the air surveillance role, the high speed of ingressing aircraft does not permit for extended integration times but typically these radars are used to cue short range SAM systems and LPI can be used to advantage in this situation. One particular case that LPI could be used effectively is in the detection of hovering

helicopters. Since there is little motion, long integration times can be used and this helps the radar to detect the target even though it is embedded within the surrounding clutter.

Examples of land based LPI radars found during this brief examination include:

- SQUIRE, (Netherlands)
- GB-SCOUT, (Netherlands)
- PAGE, (Netherlands)
- Crotale, (France)
- GRIFFON, (France)
- GERFAUT, (France)
- SENTRY, (US)
- MRSR (US)
- SHORAR, (Italy)
- HARD, (Switzerland)
- MSTAR, (UK)
- EL/M-2106, (Israel)
- EL/M-2140, (Israel)
- ARIENE, (Spain)

Power managed systems such as the French Crotale system have been placed in this LPI category. Experience has shown that Crotale is capable of quickly acquiring a target and decreasing its transmitter power to maintain a minimal SNR. This makes it very difficult for a hostile receiver to detect unless special techniques are employed. The use of a lower frequency search radar may also help with this process.

The end of the so called "Cold War" has resulted in a declining military market world-wide. There has been considerable pressure on the large military manufacturers to open up new markets and one way of doing this has been to team together to offer technology that in other times would have remained a national asset. Of particular interest is a joint upgrade program for the ageing Soviet ZSU-23-4 mobile anti-aircraft-artillery (AAA) system. This program is a joint development project supported by Signaal (Thompson-CSF) and the original manufacturer of the ZSU-23-4. The result, is a replacement of the old GUNDISH radar with a Signaal PAGE LPI surveillance set and an ASADS Ka-band tracker in a configuration reminiscent of the Dutch PRTL tank fire control system. An upgrade such as this will revitalise the lethality of this vintage weapon and will extend its useful lifetime by 15-20 years. There were between 7,000 and 8,000 ZSU-23-4 systems delivered between 1965 and 1983; many of

these systems are in active service in Africa, Asia, Eastern Europe and the Middle East. Programs such as these serve to drive home the importance of active ECM developments to counter both LPI and millimetre wave threats.

Another example of multi-national teaming is the BLAZER program in which General Dynamics Armament Division has teamed with Thompson-CSF. BLAZER consists of a Thompson TRS-2630 LPI radar, 25-mm cannon and the Mistral fire and forget missile.

It is postulated that LPI techniques will continue to be integrated into both older weapons systems through upgrades and into newer systems as they are designed. The advantages of simple power management techniques such as those used in Crotale can deny a hostile receiver detection of the radar until the target is within launch range and then there is insufficient time to initiate effective ECM.

3.4 Typical Radar Power

Due to the unclassified nature of the radar review, few details of the radars listed above were discovered. Any of the listings that gave values for transmitter power described output powers for LPI radars at less than 100 W peak and transmitters under 20 W were not uncommon. Several examples of radars with extremely low powers of less than 1 W were found. Operational ranges for these radars were typically less than 20 Km. Table 3 lists the output powers and operational ranges of several LPI radar systems found during the course of this work.

Table 3: Range and Power Characteristics of Some LPI Radar Systems

Radar	Average Power (Watts)	Range (km)
MSTAR	1 to 10	25
AN/UPS-3 SENTRY	18-20	30
TRS-2630 GRIFFON	30	20
TRS-2620 GERFAUT	20	13
P5-91 HARD	8/14	20
EL/M-2106	10	20
PAGE	20	15
ARIENE	7	20
SCOUT	0.01/0.1/1	25

4.0 LPI ECM WAVEFORMS

The major hurdle to overcome in jamming an LPI radar is to detect the signal. Having done that, conventional coherent ECM techniques should be quite effective. Having said that, LPI radars come in two general flavours; FMCW and long phase coded pulses. This section discusses some generic ECM waveforms that could be used to counter LPI radars. As with all ECM techniques, specific technique parameters would need to be developed from a knowledge of the threat radar characteristics.

4.1 FMCW

False range targets may be displayed on an FMCW radar by slightly shifting the frequency of the return. This will create a shift in the apparent range of the signal as it passes through the radar processor.

VGPO signals, which are effectively a change in the rate of change of phase of the signal, will affect the signal processing in the radar. Although the introduction of a frequency error in the return signal will affect the integration efficiency, in order to be effective, the VGPO must effectively create at least 180° phase shift over the pulse. The effect of a 180° phase shift on the performance of the coherent integrator was demonstrated in Figure 2.

Narrow-band Doppler noise may also be quite effective since the SNR in the LPI receiver is already at quite a low value. A DRFM may be used to focus the available power of the jammer and inject Doppler noise that is only a few kHz wide; i.e., tailored to the instantaneous bandwidth of the FMCW radar.

4.2 Long Pulses

An amplitude sampling DRFM will accurately record the phase history of the incoming RF signal. The limiting action of the SDLVA in the IF section of the CARDS testbed will clip the top of the waveform but many of the phase bits would remain untouched - how many would depend on the level of the incoming signal and the amount of clipping/limiting. The number of bits in the DRFM determines its dynamic range, which impacts the degree of linearity permissible, but the discussion here is about long pulses which are low power signals, so clipping should not be a serious concern. In order to quantify this

effect, it is recommended that an experiment be conducted to determine the impact of clipping on a phase coded signal. Long pulses that have been phase coded may be affected by VGPO type techniques. The introduction of an additional Doppler shift, which will be interpreted by the radar as an additional phase shift, will cause a spreading of the received signal and therefore decrease the effective processing gain. If enough Doppler shift can be added then there will be a corresponding loss of integration gain within the radar processor.

Range bin masking techniques should also be quite effective. If a section of the radar waveform is used by the jammer as its transmit waveform, the truncation will cause an increase in the sidelobe levels of the processed return. The merging of the sidelobes may create a thresholding problem for the radar leading to a blank display but at the very least will degrade the SNR of the true target return causing a loss in processing gain.

5.0 LPI JAMMER DESIGN REQUIREMENTS

Two parameters are of critical importance when considering the design of an LPI receiver front-end for ECM applications. First one must consider the RF bandwidth; too wide a bandwidth allows too much signal to enter the detector and unnecessarily degrades the receiver noise figure while too narrow a bandwidth eliminates too much of the signal lowering the average power to the detector. The second factor to be considered is the detector video bandwidth. A wide video bandwidth provides for fast rise and fall times necessary for processing narrow pulses, but this is done at the expense of allowing more noise to the detector as well. A carefully designed jammer will address both of these design areas.

Annex A and B of this report outline the calculations of the power received at both the radar and the jammer for aircraft and ship targets respectively.

5.1 RF Bandwidth

In order to define the RF bandwidth requirements for a jammer, the dynamics of the radar/target engagement must be considered. A limiting factor in this discussion is the time-bandwidth product of the radar.

A target travelling with radial velocity v_r moves a distance ΔR in the time T_I given by:

$$\Delta R = T_I \cdot v_r$$

For coherent integration, the target must not move out of the range cell during the integration time, so that:

$$\Delta R \leq \frac{c \cdot \tau}{2} \cong \frac{c}{2 \cdot B}$$ where: c = speed of light (3×10^8 m/s)

τ = pulse width

B = signal bandwidth

Therefore,

$$T_I \leq \frac{c}{2 \cdot B \cdot v_r}$$

An airborne intercept (AI) radar must be designed for closing velocities of mach2 to mach3, while a ground based radar would probably be designed for mach1 fighter aircraft or much slower closing velocities for helicopter targets. Thus, the maximum compression gain is limited to:

$$T_I \cdot B \leq 200{,}000 \qquad air - air$$
$$T_I \cdot B \leq 500{,}000 \qquad surface - air$$

Doppler resolution is equal to the inverse of the integration time, and is typically 100 to 1000 Hz. Thus T_I and B are bounded by:

$$1000 < T_I < 10{,}000 \mu s$$

$$20 < B < 500 MHz$$

This is significant in that the jammer's bandwidth should be wide enough to capture the whole radar pulse, which may be spread out over the bandwidth B by poly-phase coding, or FM chirp. The limit of modern radar technology places bounds on the amount of RF agility or chirp that can be obtained on a given radar as a function of RF operating frequency. This limit is about one half of one percent bandwidth. Therefore, for a radar operating at 10 GHz, the upper bound on either RF agility or FM chirp is on the order of 500 MHz. In practice, the operational limit is somewhat smaller than this due to the need of matching RF components over this significant bandwidth and over the rigorous military environment constraints.

5.2 Video Bandwidth

The primary LPI technique employed by radar designers is to spread the signal in frequency and use coherent integration and pulse compression so that the radar's peak radiated power can be reduced to the point where the signal power levels at the jammer are lost in the noise. If the jammer attempts to narrow its bandwidth in order to reduce the noise power, it loses a significant amount of

the information because of the radar's large agile bandwidth. The main problem for the jammer, therefore, is simply to detect the radar signal. Calculations made by Dr. Jim Lee, Ref. (6), show that in order to detect an LPI radar, the receiver sensitivity must be on the order of -100 dBm. Even with a coherent jammer such as CARDS that has been designed with a low noise front-end, this is well down in the noise floor. Thus, it is necessary to devise a way to improve the jammer's minimum detectable signal level. In order to quantify the amount of improvement required, a closer look at the radar range equation is warranted. It will then be possible to estimate the potential of various strategies to improve the jammer's minimum detectable signal (MDS) performance and the impact these will have on other areas of its performance.

The radar range equation will be used for both the radar and the jammer to determine what factors are determining the detection range of the target and of the radar.

5.2.1 Radar calculations

Assume path losses from the transmitter section to the antenna of L_{Rt}, from the antenna to the receiver of L_{Rr} and common antenna of gain G_R. The signal power received by the radar from the target is:

$$P_{Rr} = P_t \cdot L_{Rt} \cdot G_R \cdot \frac{1}{4\pi R^2} \cdot \sigma \cdot \frac{1}{4\pi R^2} \cdot \frac{G_R \lambda^2}{4\pi} \cdot L_{Rr} \qquad (1)$$

At maximum detection range, eqn. (1) can be rewritten as:

$$R_{R\max}^4 = \frac{P_t \cdot L_{Rt} \cdot L_{Rr} \cdot G_R^2 \cdot \sigma \cdot \lambda^2}{(4\pi)^3 \cdot P_{Rr\min}} \qquad (2)$$

where:

$$P_{Rr\min} = \frac{K \cdot T \cdot B_R \cdot F_R \cdot SNR_{R\min}}{G_C} \qquad (3)$$

In the above equation, G_C is the compression gain, achieved through the use of a linear FM chirp or poly-phase coding. The radar bandwidth is approximately the inverse of the pulse width, which in a pulse compression radar is the compressed pulse width. The compression gain, G_C, is defined as:

$$G_C = B_R \cdot T_I \tag{4}$$

where T_I is the coherent integration period of the radar; i.e., the uncompressed pulse width or the chirp period for an FMCW radar. The inverse of T_I is the effective noise bandwidth of the radar, B_{NR}. For poly-phase coding, B_R is the inverse of the sub-pulse width, and for linear FM chirp, B_R is the chirp bandwidth. Thus, eqn. (3) can be rewritten as:

$$P_{Rmin} = K \cdot T \cdot B_{NR} \cdot F_R \cdot SNR_{Rmin} \tag{5}$$

For a Swerling 1 or 2 target, which would be appropriate for a ship, the minimum signal to noise ratio required for 90% detection with 10^{-6} probability of false alarm, is 21 dB. The probability of false alarm is based on a false alarm interval, t_{fa}, of one hour and a final bandwidth, B, of 1 kHz, and is calculated from:

$$P_{fa} = \frac{1}{t_{fa} \cdot B} \tag{6}$$

An aircraft target being engaged head-on is represented by a Swerling 3 or 4 characteristic and the minimum SNR is 17 dB. In the above equations, K is Boltzman's constant, T is the temperature in degrees Kelvin and F_R is the input noise figure of the radar. For a 1 kHz bandwidth at room temperature, KTB = -144 dBm.

Table 4 shows the relative losses the radar must deal with when compared to the non-fluctuating return that the jammer is presented with. "N" represents the number of pulses that are being integrated.

Table 4: Fluctuation Loss Relative to Non-fluctuating Target (dB)

N	Swerling 1	Swerling 2	Swerling 3	Swerling 4
1	8.0	8.0	3.9	3.9
10	8.3	0.8	4.1	0.5
100	8.5	0.4	4.6	0.1
1000	8.7	0.2	4.8	0

Note: Detection probability = 0.9; false alarm probability = 10^{-6}.

It is interesting to note that the 8 or 9 dB loss associate with the Swerling 1 case (which represents many ship target applications) cannot be overcome with additional integration. Similarly, the Swerling 3 case shows a loss of about 4 to 5 dB for a typical airborne target that cannot be overcome with integration. This is a significant advantage for the jammer and helps to show that it is indeed quite difficult for the radar designer to develop a truly quiet radar.

5.2.2 Jammer calculations

The jammer has basically the same problems in detecting the signal as the radar does, although the signal is essentially non-fluctuating, which reduces the SNR requirement somewhat. Accounting for polarization mismatch and line loss from the antenna to the jammer front end in a global loss factor, L_J, the received power is:

$$P_{Jr} = P_t \cdot L_{Rt} \cdot G_R \cdot \frac{1}{4\pi R^2} \cdot \frac{G_J \lambda^2}{4\pi} \cdot L_J \tag{7}$$

Rearranging, the maximum range at which the jammer can detect the radar signal is given by:

$$R^2_{J\max} = \frac{P_t \cdot L_{Rt} \cdot G_R \cdot G_J \cdot L_J \cdot \lambda^2}{(4\pi)^2 \cdot P_{Jr\min}} \tag{8}$$

where

$$P_{Jr\min} = K \cdot T \cdot B_J \cdot F_J \cdot SNR_{J\min} \tag{9}$$

One way to increase the jammer's sensitivity is to reduce its effective noise bandwidth. If the video bandwidth is less than half the RF bandwidth, then the effective noise bandwidth is given by:

$$B_e = 0.4\sqrt{2 \cdot B_{RF} \cdot B_V} \tag{10}$$

From eqn. (10), this can best be accomplished by reducing the video detection bandwidth, B_V. This has the effect of increasing the detector rise time:

$$t_r = \frac{0.35}{B_V} \tag{11}$$

The Menlo SDLVA currently used in the CARDS RF sub-system has a video bandwidth of 40 MHz, which leads to its fast rise time of 9 ns. For the LPI application however, the pulses are typically very long and the duty cycle is generally between 50 and 100%, so fast rise times are not required. Therefore, two methods are immediately open for improving the sensitivity of the jammer: reduction of the RF bandwidth and reduction of the video bandwidth.

With a video bandwidth of 100 kHz, the rise time would be 3.5 μs. Assuming a 400 MHz RF bandwidth for the jammer, its effective noise bandwidth would be 3.6 MHz and KTB would be -108 dBm. The probability of false alarm from eqn. (6) is approximately 10^{-10}, assuming the same false alarm interval of one hour. If the same probability of detection is assumed for the jammer as for the radar, i.e., 90%, then the minimum SNR required for the jammer is 15 dB.

5.2.3 Comparison of Jammer and Radar Maximum Detection Ranges

By squaring eqn. (8) and dividing by eqn. (2), it is possible to compare the radar's maximum target detection range with the jammer's maximum radar signal detection range:

$$\left(\frac{R_{J\max}}{R_{R\max}}\right)^4 = \frac{P_t \cdot L_{Rt} \cdot G_J^2 \cdot L_J^2 \cdot \lambda^2 \cdot P_{Rr\min}}{L_{Rr} \cdot 4\pi \cdot \sigma \cdot P_{Jr\max}^2} \tag{12}$$

If it is assumed that the receive and transmit losses for the radar are approximately equal, eqn. (9) can be simplified to:

$$\left(\frac{R_{J\max}}{R_{R\max}}\right)^4 = \frac{P_t \cdot L_J^2 \cdot \lambda^2 \cdot G_J^2}{4\pi \cdot \sigma \cdot K \cdot T \cdot B_{NJ}} \cdot \frac{B_{NR}}{B_{NJ}} \cdot \frac{F_R}{F_J^2} \cdot \frac{SNR_{R\min}}{SNR_{J\min}^2} \tag{13}$$

In order for the jammer to be able to detect the radar signal at a range greater than the radar's maximum detection range, the right hand side of eqn. (13) must be greater than 1. Converting to log form, substituting the values for SNR from the above discussions and assuming typical noise figures of 8 and 12 dB for the radar and the jammer respectively, eqn. (13) becomes:

$$10\log P_t + 20\log(L_J \cdot \lambda \cdot G_J) + 10\log B_{NR} - 20\log B_{NJ} - \sigma + 57 + SNR_{R\min} > 0 \quad (14)$$

Hence:

$$2 \cdot B_{NJ} < P_t + 2 \cdot L_J + 2 \cdot \lambda + 2 \cdot G_J + B_{NR} + 74 - \sigma \quad \text{aircraft targets} \quad (15a)$$

$$2 \cdot B_{NJ} < P_t + 2 \cdot L_J + 2 \cdot \lambda + 2 \cdot G_J + B_{NR} + 78 - \sigma \quad \text{ship targets} \quad (15b)$$

where B_{NJ} and B_{NR} are in MHz.

To illustrate the significance of eqn. (15), consider two radars, one at X-band (9 GHz) designed for an aircraft target and the other at K-band (35 GHz) designed for a ship target. If the following assumptions are made:

- the aircraft RCS is 0 dBm^2,
- the ship RCS is 30 dBm^2,
- jammer losses are assumed to be 5 dB,
- P_t is 1W (+30 dBm) in both cases,
- jammer antenna gain is zero, and
- the radar effective noise bandwidth is assumed to be 100 Hz or –40 dB (MHz),

then the radar's maximum range will be 18 km in the air scenario and 75 km in the naval scenario. The jammer will be able to detect the radar at this maximum range if the effective noise bandwidth of the jammer is less than 16 MHz for the air case, and less than 250 kHz for the anti-ship case.

From eqn. (10), these bandwidths can be achieved with video bandwidths of 2 MHz and 5 kHz, for the air and maritime cases respectively. Note that it has been assumed that the jammer antenna is omni-directional. In the airborne scenario it is not uncommon for the antenna gain to be sufficient to offset the polarization and waveguide losses, and RAMSES is a prime example of a naval jammer which employs significant antenna gain, estimated to be about 30 dB. Although it is not practical to use a video detector bandwidth of 5 kHz, it may be practical to add jammer antenna gain, as is currently the case with RAMSES. A jammer antenna gain of only 10 dB would change the required effective noise bandwidth of the jammer to 2.5 MHz, which could be achieved with a video bandwidth of about 50 kHz.

Of course, reduction of the video bandwidth is not the only possibility for improving the jammer sensitivity. The RF bandwidth can also be reduced. Unfortunately, reducing the bandwidth does come with a cost. In order to accommodate the wide range of agile bandwidths seen in modern radar systems, the video processing hardware in the jammer IF would need to be duplicated each time the RF bandwidth is halved. Current cost estimates of the detector SDLVA are about $7000 making it an expensive proposition to create multiple parallel RF channels.

Acousto-optical technology (AO) is being investigated for detection of LPI radars in electronic support measure (ESM) applications. AO technology has a definite benefit for ESM in that direction of arrival (DOA) information can be readily gained by the processor. Unfortunately for ECM applications that generally do not require accurate angle information, the cost of this benefit can be measured in monetary terms. Ristic, Ref. 12, estimated the cost of a 500 MHz AO processor at about $500k – adding this technology would almost double the cost of a conventional jammer.

6.0 CONCLUSIONS

There are a significant number of examples of LPI radars currently in use in a variety of land, air and maritime applications. Due to target motion, air applications of LPI radar appear to be quite limited but do exist nonetheless; the most common air application being covert navigation.

In the maritime environment, covert navigation is also a prime application however, the use of LPI technology in anti-ship missile seekers appears to be a promising development. In this case, the large radar cross-section of the ship target combines with its slow speed to permit the ASM to obtain long integration times and therefore considerable processing gain. This will force future jammer to develop a means of detecting in-coming missiles that, will current ECM technology, may not become visible until they seconds from impact

LPI radar techniques come in several flavours. Pulse compression techniques such as linear FM (or FMCW) and phase coded pulses can be used to reduce the peak power of a pulse while maintaining the desired range resolution and average power in the waveform.

Linear FM modulated signals have small instantaneous bandwidths and therefore can be detected using a narrow bandwidth receiver. These waveforms are not programmable and, simply by measuring the characteristics of a short segment of the chirp, a hostile receiver is able to obtain processing gain similar to that of the radar.

Binary phase coded waveforms can be designed to be "noise-like" in appearance but this characteristic can be removed using frequency doubling techniques.

Poly-phase coded techniques will be the waveform of choice as LPI radar technology advances. Fortunately for the jammer, the resulting pulses are quite wide allowing the jammer to reduce its effective bandwidth by narrowing the video detection bandwidth. Poly-phase codes will also require modifications to the way that the signal is down-converted for processing. The use of a limiter in the receiver IF chain as is currently done in the CARDS testbed will cause some of the phase modulation characteristics to be lost as the signal is "clipped" in this stage.

It has been shown that it is quite difficult to design a truly quiet radar. For this to be true, the radar's target must be slow moving – to allow for a long integration time, it must be quite large – to reduce the need for high levels of processing gain and the engagement range must be quite short – in order to minimise the range advantage (ie $P_{R,jammer} / P_{R,radar} \propto R^2$). In addition, the radar frequently must deal with a reduction in SNR that accompanies a fluctuating target. This can give the jammer as much as an 8 dB advantage.

It has been shown that narrowing of either the jammers RF bandwidth or the video bandwidth will yield some improvement in sensitivity. In order to be able to cover the wide agile bandwidth seen by modern radars, as the RF bandwidth is narrowed, the number of parallel channels must be increased. This becomes quite costly due to the use of SDLVA technology in each of the parallel receive channels.

It has been proposed that, by careful design, an improved video detector may be developed that takes into consideration the relatively long pulses involved with the use of LPI radar technology and uses this fact to reduce the video bandwidth of the detector to achieve significant improvements in jammer noise levels.

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ANNEX A – POWER LEVEL CALCULATIONS - AIRCRAFT TARGET

The following exercise was undertaken to demonstrate that not only was LPI radar feasible from a radar point of view but also to demonstrate that detection of these radars by an ECM system was not an impossible task.

The radar range equation was used to calculated the values in Table 5 which shows the power levels (P_r) received at a radar from a small aircraft target (RCS = $1m^2$) for various radar ERP and range values at both 9 GHz and 35 GHz operating frequencies. For the purposes of this analysis atmospheric attenuation (due to O_2 and H_2O) has been ignored.

Table 5: Target Signal Power Received at Radar

		I-Band			Ka-Band		
Parameter	**Units**	**Vary ERP & Range**			**Vary ERP & Range**		
Pt	dBm	30	43	50	30	30	30
Gr	dB	37	37	37	45	50	55
ERP	dBm	67	80	87	75	80	85
RCS (Sigma)	dBm^2)	0	0	0	0	0	0
RF (f)	GHz	9	9	9	35	35	35
Lamda=10*log(0.3/f)	dBm	-15	-15	-15	-21	-21	-21
log(4*PI)	dB	11	11	11	11	11	11
R (maximum)	km	18	25	40	15	30	50
40*log(R*1000)	dBm	170	176	184	167	179	188
Pr	dBm	-129	-121	-123	-121	-123	-122

For a radar performing Doppler processing with a resolution of 100Hz, the minimum detectable signal (MDS) at the radar will be:

$$\text{Radar MDS} = -114+10*\log(BW)+SNR+NF$$

Where: BW is the final processing bandwidth of the radar (100Hz)
SNR is the signal to noise ratio required for detection
NF is the radar noise figure

Aircraft targets are generally classified as Swerling Type 3 fluctuating targets; the SNR at the radar required to detect an aircraft target can be obtained from Figure 4. If the desired probability of detection is 90% and the probability of false alarm is taken to be 10^{-6}, then the required SNR is 17 dB. If a typical

radar noise figure is assumed to be 8 dB then the resulting MDS of the radar is calculated to be –129 dBm.

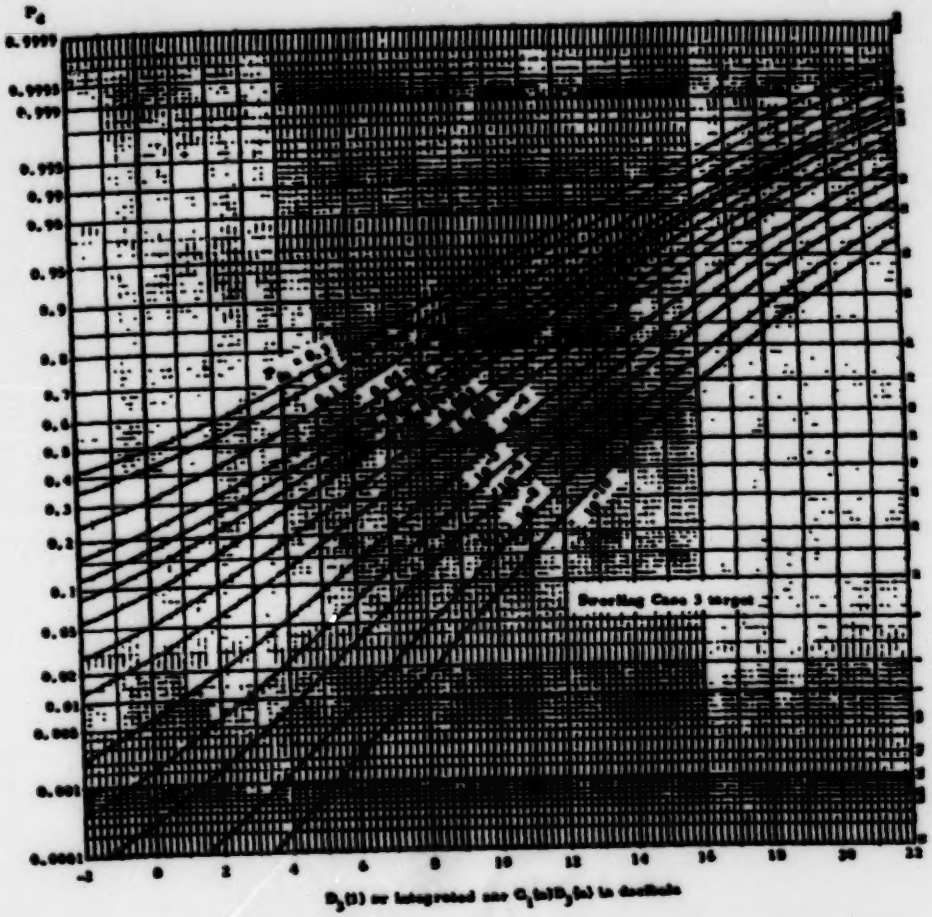

Figure 4: Signal to Noise Ratio Required for Detection of Aircraft

This result shows that for the conditions shown in Table 5 the radar will be capable of detecting its intended targets.

A similar analysis to calculate the power received by the jammer can be made using the radar range equation. If a jammer antenna gain is allowed to vary

between 0 and 5 dB and a 5 dB jammer loss is assumed then the power received at the jammer is shown in Table 6.

Table 6: Power Levels Received at Jammer

		I-Band			Ka-Band		
Parameter	**Units**	**Vary ERP+Range**			**Vary ERP+Range**		
Radar ERP	DBm	67	80	87	75	80	85
Range	Km	18	25	40	15	30	50
Gj	DB	0	5	5	0	5	5
Lp	DB	5	5	5	5	5	5
Prj	DBm	-75	-59	-57	-77	-73	-72

It should be noted that these power levels are considerably lower than is currently detectable by the current CARDS RF sub-system. The question that comes to mind is then, can something be done to improve the sensitivity of the system.

It is possible to calculate the required effective jammer bandwidth in order to be able to detect the radar under the conditions described above. As described in the main body of the report, the effective noise bandwidth is a function of both the RF bandwidth and the video bandwidth. From this information, the required video bandwidth can be calculated. For the purposes of this analysis, the jammer noise figure is assumed to be 12 dB and the jammer RF bandwidth is assumed to be 400 MHz. As with the radar, the time between false alarms is selected to be 1 per hour. The probability of false alarm under these conditions is 10^{-10}.

The jammer has an advantage in that, unlike the radar which must process returns with fluctuating characteristics, the received power levels are non-fluctuating in nature. In this case, the Rice curves of Figure 5 are used determine the required SNR for detection. In this case an SNR of 15 dB satisfies the requirements.

The required video bandwidth for a matched receiver is taken to be one half of the RF bandwidth. This is an ideal situation. As the video bandwidth is narrowed, the rise time response from the detection circuitry degrades. The above information is used to determine the required jammer video bandwidth in

order to detect the radar at its maximum operating range. The results are shown in Table 7. The results of these calculations show that, with an RF bandwidth of 400 MHz at I-band to permit jamming of radars with frequency agility, the use of a 2.2 MHz video bandwidth would allow detection of the LPI radars at their maximum operating ranges. At Ka-band the video bandwidth requirement decreases to 100 kHz.

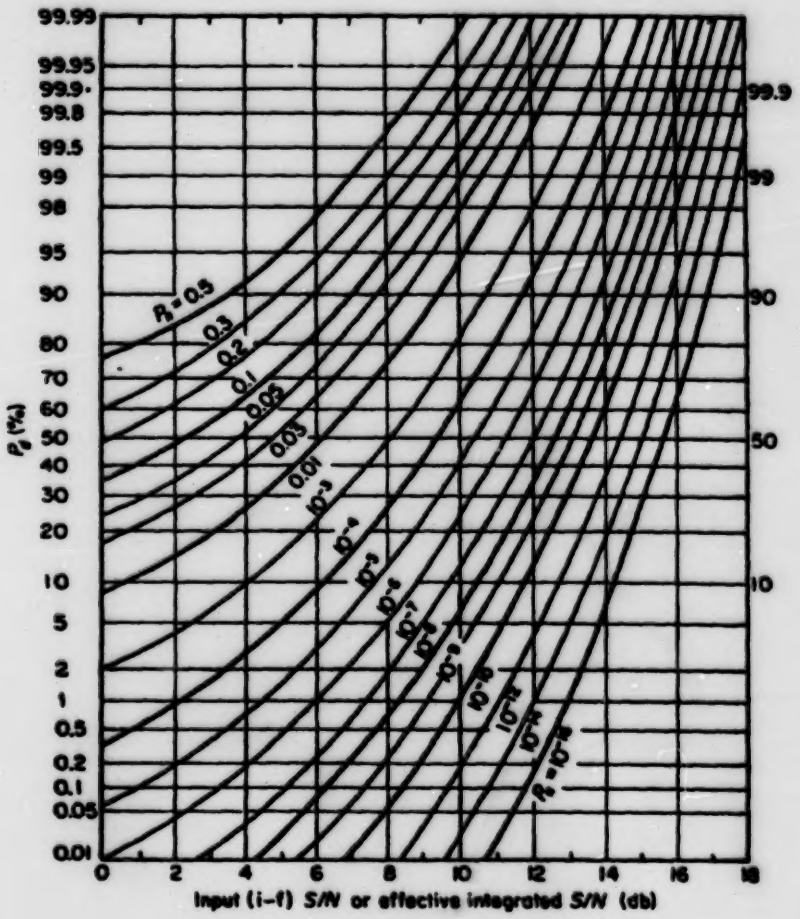

Figure 5: Rice Curves

Table 7: Jammer Video Bandwidth Requirement Calculation

		I-Band				Ka-Band	
Parameter	**Units**	**Vary ERP**				**Vary Gj**	
Pt	dBm	30	43	50		30	30
Lj	dB	5	5	5		5	5
Gj	dB	0	5	5		0	5
RF (f)	GHz	9	9	9		35	35
Lamda=10*log(0.3/f)	dBm	-15	-15	-15		-21	-21
4PI	dB	11	11	11		11	11
RCS (Sigma)	dBm^2	0	0	0		0	0
KTB (1MHz)	dBm	-114	-114	-114		-114	-114
Bnr	dBMHz	-40	-40	-40		-40	-40
NFr	dB	8	8	8		8	8
NFj	dB	12	12	12		12	12
SNRrmin	dBm	17	17	17		17	17
SNRjmin	dBm	15	15	15		15	15
Bnj	dBMHz	12.2	23.7	27.2		6.3	11.3
Bnj (max)	MHz	16.7	236.0	528.3		4.3	13.6
Brfj	MHz	400.0	400.0	400.0		400.0	400.0
Bvj (max)	MHz	2.2	200.0	200.0		0.1	1.4

These calculations suggest that with narrow, but useable, video bandwidths on the order of one MHz, and only 5 dB of jammer antenna gain, it should be possible to detect LPI radars with ERP of only one Watt. This includes the MMW radars that have an inherent 12 dB advantage over the X-band radars.

ANNEX B – POWER LEVEL CALCULATIONS – SHIP TARGET

In a similar fashion to the analysis performed in Annex A which dealt with an aircraft target, the following exercise was undertaken assuming a ship target.

The radar range equation was used to calculated the values in Table 8 which shows the power levels (P_r) received at a radar from a typical ship target (RCS = 1000 m^2) for various radar ERP and range values at both 9 GHz and 35 GHz operating frequencies. For the purposes of this analysis atmospheric attenuation (due to O_2 and H_2O) has been ignored.

Table 8: Target Signal Power Received at Radar

		I-Band			Ka-Band		
Parameter	**Units**	**Vary ERP & Range**			**Vary ERP & Range**		
Pt	dBm	30	43	50	30	30	30
Gr	dB	37	37	37	45	50	55
ERP	dBm	67	80	87	75	80	85
RCS (Sigma)	dBm^2)	30	30	30	30	30	30
RF (f)	GHz	9	9	9	35	35	35
Lamda=10*log(0.3/f)	dBm	-15	-15	-15	-21	-21	-21
log(4*PI)	dB	11	11	11	11	11	11
R (maximum)	km	18	25	40	15	30	50
40*log(R*1000)	dBm	170	176	184	167	179	188
Pr	dBm	-99	-91	-93	-91	-93	-92

For a radar using a 10 ms integration period, the minimum detectable signal (MDS) at the radar will be:

$$\text{Radar MDS} = -114+10*\log(BW)+SNR+NF$$

Where: BW is the final processing bandwidth of the radar (100Hz)
SNR is the signal to noise ratio required for detection
NF is the radar noise figure

Ship targets are generally classified as Swerling Type 1 fluctuating targets; the SNR at the radar required to detect a ship target can be obtained from Figure 6. If the desired probability of detection is 90% and the probability of false alarm is taken to be 10^{-6}, then the required SNR is 21 dB. If a typical radar noise

figure is assumed to be 8 dB then the resulting MDS of the radar is calculated to be –125 dBm.

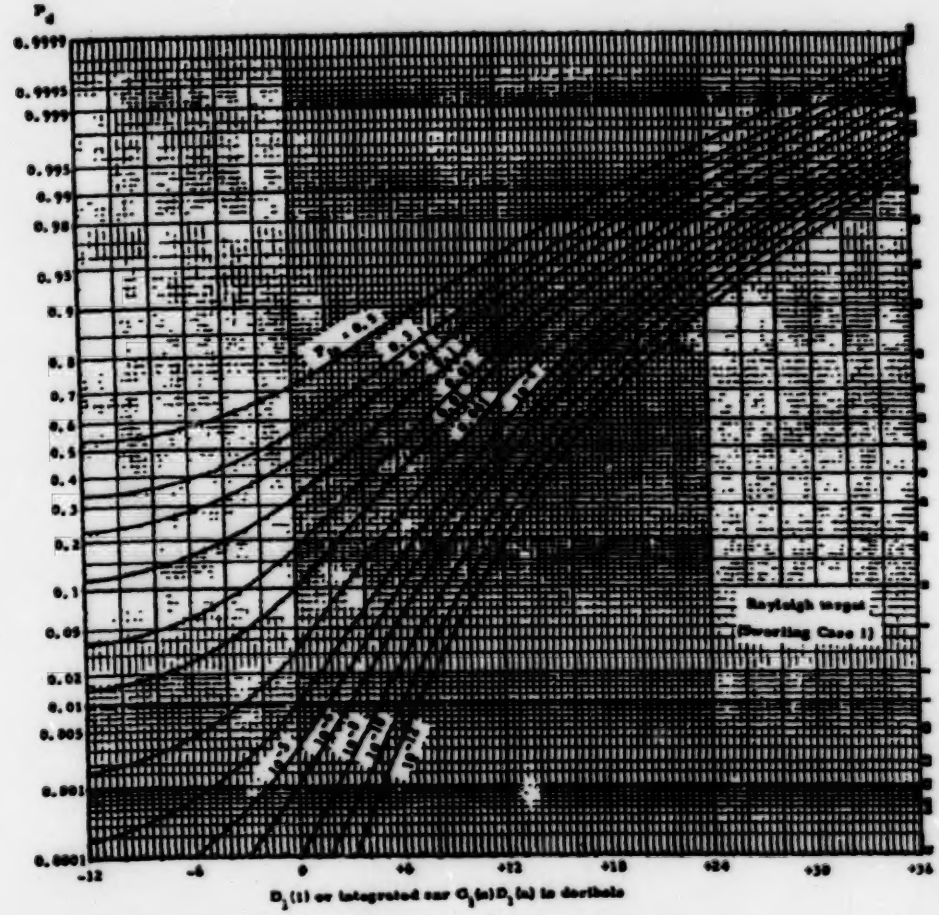

Figure 6: Signal to Noise Ratio Required for Detection of Ships

This result shows that for the conditions shown in Table 8 the radar will be capable of detecting its intended targets.

A similar analysis to calculate the power received by the jammer can be made using the radar range equation. If a jammer antenna gain is assumed to be 5 dB

and a 5 dB jammer loss is assumed then the power received at the jammer is shown in Table 9.

Table 9: Power Levels Received at Jammer

		I-Band			Ka-Band		
Parameter	**Units**	**Vary ERP+Range**			**Vary ERP+Range**		
Radar ERP	dBm	67	80	87	75	80	85
Range	km	18	25	40	15	30	50
Gj	dB	5	5	5	5	5	5
Lp	dB	5	5	5	5	5	5
Prj	dBm	-70	-59	-57	-72	-73	-72

It should be noted that these power levels are considerably lower than is currently detectable by the current CARDS RF sub-system. The question that comes to mind is then, can something be done to improve the sensitivity of the system.

It is possible to calculate the required effective jammer bandwidth in order to be able to detect the radar under the conditions described above. As described in the main body of the report, the effective noise bandwidth is a function of both the RF bandwidth and the video bandwidth. From this information, the required video bandwidth can be calculated. For the purposes of this analysis, the jammer noise figure is assumed to be 12 dB and the jammer RF bandwidth is assumed to be 400 MHz. As with the radar, the time between false alarms is selected to be 1 per hour. The probability of false alarm under these conditions is 10^{-10}.

The jammer has an advantage in that, unlike the radar which must process returns with fluctuating characteristics, the received power levels are non-fluctuating in nature. In this case, the Rice curves of Figure 5 are used determine the required SNR for detection. In this case an SNR of 15 dB satisfies the requirements.

The above information is used to determine the required jammer video bandwidth in order to detect the radar at its maximum operating range. The results are shown in Table 10. The results of these calculations show that, with an RF bandwidth of 400 MHz at I-band to permit jamming of radars with

frequency agility, the use of a 55 kHz video bandwidth would allow detection of the LPI radars at their maximum operating ranges. At Ka-band the video bandwidth requirement decreases to 3.6 kHz.

Table 10: Jammer Video Bandwidth Calculations

		I-Band			Ka-Band		
Parameter	**Units**	**Vary ERP**			**Vary Jammer Ant. Gain**		
Pt	dBm	30	43	50	30	30	30
Lj	dB	5	5	5	5	5	5
Gj	dB	5	5	5	5	10	15
RF (f)	GHz	9	9	9	35	35	35
Lamda=10*log(0.3/f)	dBm	-15	-15	-15	-21	-21	-21
Log(4*PI)	dB	11	11	11	11	11	11
RCS (Sigma)	dBm^2	30	30	30	30	30	30
KTB (1MHz)	dBm	-114	-114	-114	-114	-114	-114
Bnr	dBMHz	-40	-40	-40	-40	-40	-40
NFr	dB	8	8	8	8	8	8
NFj	dB	12	12	12	12	12	12
SNRrmin	dBm	21	21	21	21	21	21
SNRjmin	dBm	15	15	15	15	15	15
Bnj	dBMHz	4.2	10.7	14.2	-1.7	3.3	8.3
Bnj (max)	MHz	2.6	11.8	26.5	0.7	2.2	6.8
Brfj	MHz	400.0	400.0	400.0	400.0	400.0	400.0
Bvj (max)	MHz	0.0548	1.0928	5.4771	0.0036	0.0362	0.3622

Video bandwidths of less than 350 kHz are likely to be deemed impractical due to the effect on detector rise time: narrower bandwidths than this result in rise times in excess of 1 μs. In the maritime case, it is possible to reduce the requirement on the video filter if additional antenna gain can be supplied. Table 10 shows the effect of antenna gain at Ka-band: an increase in antenna gain from 5 dB to 15 dB results in a required video bandwidth of 362 kHz as opposed to the far more impractical 3.6 kHz.

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Low Probability of Intercept (LPI) radar describes a class of radars that have been purposefully designed to be difficult to detect by hostile receivers. This report summarizes some of the LPI techniques and gives examples of currently fielded LPI radars. Several options are investigated that may help a jammer designer develop an architecture that can lead to a capability to detect and jam LPI radars.

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ECM
electronic countermeasures
jammers
jamming
low probability of intercept
LPI radars
radar countermeasures

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